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Flame temperature distribution in a pool-fire

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Abstract

The variation of flame temperature with time and height (for the initial steps as well as for fully developed fire) has been studied in hydrocarbon pool-fires. Experimental data (temperatures measured with thermocouples and radiometers) measured with hexane (4 m^2) and kerosene (12 m^2) pool-fires were used to obtain the value of flame temperature. A significant difficulty was found to deduce this parameter from experimental values. A correlation is proposed to predict flame temperature as a function of time and height. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Flame temperature; Pool-fires; Hexane; Kerosene

1. Introduction

Fire accidents form an important part of all accidents which occur in the chemical industry and in the transport of hazardous materials: fire is involved in 41.4% of all these events, according to a historical analysis based on a survey of 6099 cases [1]. The same analysis shows that of the different types of fire (jet fire, flash fire, etc.), pool fire is the most frequent. This is in good agreement with the fact that liquids were involved in 53% of accidents.

Although the direct effects of a pool-fire cover a smaller area than other major accidents (for example, BLEVE or gas clouds), the action of flames on process

Abbreviations: a, Constant in Eq. (1) (−); b, Constant in Eq. (1) (−); F, View factor (−); h, Height from pool surface (m); H_R, Relative humidity in the atmosphere (%); P_w, Partial pressure of water vapour in the atmosphere (Pa); Q, Radiant heat flux (W m^{-2}); T, Temperature (K); t, Time since ignition (s); x, Distance between the flame surface and the target (m); f, Flame; a, Room; σ, Stefan–Boltzmann constant ($5.67 \cdot 10^{-8}$ W m^{-2} K^{-4}); τ, Atmospheric transmissivity (−)

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equipment can result in further escapes of hazardous substances and cause a much more serious accident. The situation becomes especially dangerous if the flames impinge on the surface of equipment, as in this case the heat flux is very high.

A good knowledge of the phenomenon is required to make an effective analysis of these situations. Diverse authors have made experimental studies of the main features of pool-fires, and a few of them have attempted mathematical modelling. A brief review of these publications has recently been published [2]. Practically all these communications have been devoted to fully developed fires; the first transitory period, i.e. that corresponding to the growth and development of a pool-fire, has only been analysed in one of these communications [3]. Nevertheless, this first step—which usually lasts approximately 1 minute—is very important because heat fluxes can reach very high values and even cause extremely rapid failure of the equipment (for example, the first BLEVE in the accident of Mexico City occurred after 69 s of fire ignition).

Furthermore, most of the authors considered flame temperature as being constant with time (steady state) and height. This simplifying assumption introduces an error which should be corrected if a better modelling of the phenomenon is desired.

This work deals with the variation of flame temperature in a pool-fire as a function of time and height. Experimental data obtained from pool-fires of 4 m^2 and 12 m^2 are used to obtain a correlation allowing an estimate to be made of flame temperature.

2. Experimental data

A detailed description of the experimental set-up has been published elsewhere [3]. Large-scale tests were conducted in pool-fires in which a horizontal cylindrical tank was

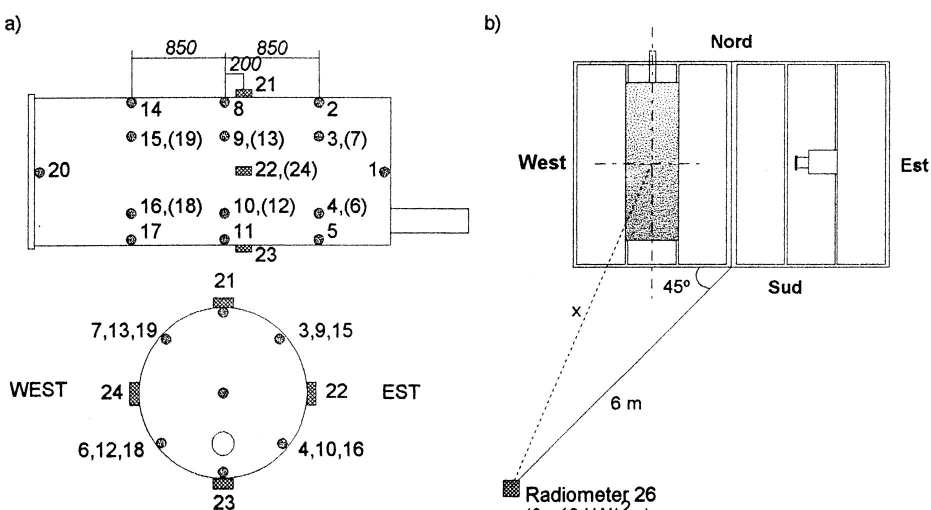


Fig. 1. Experimental set-up. (a) Rectangular thermocouples (21, 22, 23, 24) correspond to thermocouples measuring flame temperature. (b) Radiometer located at 6 m from the experimental set-up.

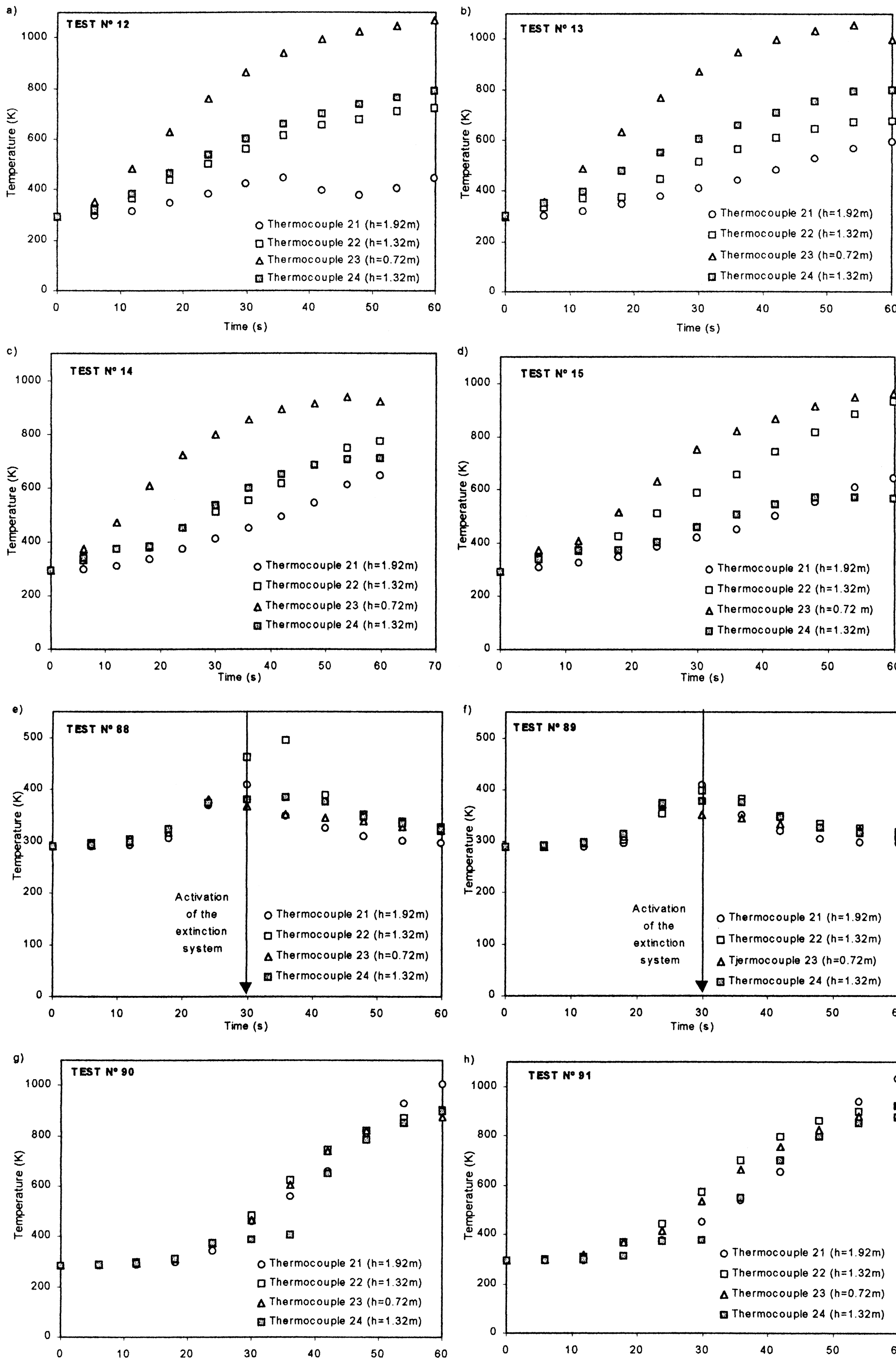
engulfed in the fire. Flame temperature was measured at four points, corresponding to three different heights on the external wall of the tank (see Fig. 1). These points were located at a height of 0.72 m, 1.32 m (two measurements) and 1.92 m from the pool surface. Plate thermocouples were used (numbers 21, 22, 23 and 24 in Fig. 1). These consisted in a stainless steel box (100 mm × 100 mm × 15 mm) with a thermocouple welded to the inside surface of the frontal wall; the box was packed with insulating material (these thermocouples had been developed by S.P. (Division of Fire Technology) at Böras. Tests were carried out with hexane (with a pool surface of 4 m^2) and kerosene (with a pool surface of 12 m^2). Fig. 2 shows the experimental results corresponding to the measurement of flame temperature.

Measurements were also performed on the thermal radiation originating from the fire using a radiometer (Medtherm type, operating in the 1–20 kW m^{-2} range).

3. Results

A total of eight tests were carried out using hexane and kerosene pools. The results showed high reproducibility, so average values were used to simplify the correlation. These values have been plotted in Fig. 2, which shows the evolution of temperature as a function of time for the three heights (0.72 m, 1.32 m, 1.92 m) and tests 12, 13, 14, 15 (hexane, 4 m^2) and 88, 89, 90, 91 (kerosene, 12 m^2). The results corresponding to hexane pool-fires show a significant variation from one height to another, the value of the flame temperature decreased with height. After a very short period (approximately 3 s) corresponding to the first step (ignition), an increase of temperature as a function of time can be seen in all cases. After approximately 1 min, the steady state was reached; from that moment, flame temperatures were approximately constant. In several tests (for example, tests 13 and 15) the temperature distribution was not symmetrical due to the action of induced wind, which moved the flames towards one of the sides of the tank.

In the case of kerosene pool-fires (12 m^2, tests 88, 89, 90 and 91), the temperatures measured were much closer, and a significant effect of height could not be observed. This is probably due to the considerable turbulence existing in these larger fires; furthermore, the measuring points in the experimental facility used were located in such a position that they covered only a limited zone of these very large fires. Other factors that could contribute to this more uniform temperature distribution are a higher heat transfer within the flame due to increased soot production, and the slower chemistry in the combustion of kerosene compared to hexane. Again, flame temperature increased with time, due to the development of fire. The first step, following ignition and corresponding to the time required for fire to cover all the pool, was now longer (approximately 12 s) as pool surface was larger. For these tests, the time during which temperatures were measured (the first minute, as for hexane pool-fires) was in fact lightly shorter than the time required for the complete fire development; in two of the tests (number 88 and 89) the extinction system was activated after 30 s from ignition, and thus flame temperature decreased from that moment (the target of the experimental work was the use of foam and water to cool the equipment and extinguish pool fires during the early stages of fire development).


a)
TEST N° 12
Temperature (K)
Time (s)
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)
b)
TEST N° 13
Temperature (K)
Time (s)
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)
c)
TEST N° 14
Temperature (K)
Time (s)
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)
d)
TEST N° 15
Temperature (K)
Time (s)
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72 m)
Thermocouple 24 (h=1.32m)
e)
TEST N° 88
Temperature (K)
Time (s)
Activation of the extinction system
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)
f)
TEST N° 89
Temperature (K)
Time (s)
Activation of the extinction system
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Tjermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)
g)
TEST N° 90
Temperature (K)
Time (s)
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)
h)
TEST N° 91
Temperature (K)
Time (s)
Thermocouple 21 (h=1.92m)
Thermocouple 22 (h=1.32m)
Thermocouple 23 (h=0.72m)
Thermocouple 24 (h=1.32m)

4. Correlation of results

The tendency of experimental values was a reciprocal of a hyperbola with the following general equation [4]:

$$y = \frac{x}{a \cdot x + b} \tag{1}$$

The experimental data were used to find the best values for the constants a and b.

4.1. Kerosene pool-fire (12 m^2)

The correlations finally obtained for kerosene pools were:

$$T_f(t, h = 0.72)\ \frac{t}{0.000309 \cdot t + 0.0453} \tag{2a}$$

$$T_f(t, h = 1.32) = \frac{t}{0.00026 \cdot t + 0.0449} \tag{2b}$$

$$T_f(t, h = 1.92) = \frac{t}{0.000084 \cdot t + 0.059} \tag{2c}$$

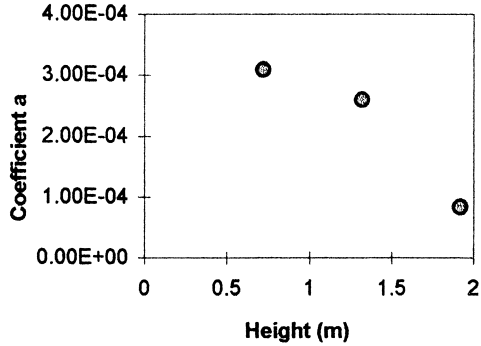
These three expressions give flame temperature as a function of time, at a constant height. In order to obtain a single equation allowing an estimate of flame temperature as a function of time and height, the various coefficients were correlated as a function of height. The variation of the coefficients with height for kerosene pools is shown in Fig. 3. As only three points were available, a lineal correlation was selected. The following expression was finally obtained:

$$T_f(t, h) = \frac{t}{(0.000465 - 0.000188 \cdot h) \cdot t + 0.0114 \cdot h + 0.0347} \tag{3}$$

The values predicted by this relationship have been plotted in Fig. 4, together with the experimental results. The agreement of this equation with the experimental data is extremely good. However, Eq. (3) cannot be applied at $t < 15$ s, as the predicted values have no physical meaning: temperature tends to zero instead of to room temperature; this deviation is corrected in the last part of this paper.

Fig. 2. Experimental results corresponding to flame temperature. White points correspond to the average value at each moment for tests 12, 13, 14 and 15. Grey points correspond to the average values at each moment for tests, 88, 89, 90 and 91.

Height (m)	Coefficient a
0.72	3.09E-04
1.32	2.60E-04
1.92	8.40E-05



Height (m)	Coefficient b
0.72	0.045304
1.32	0.04486
1.92	0.058976

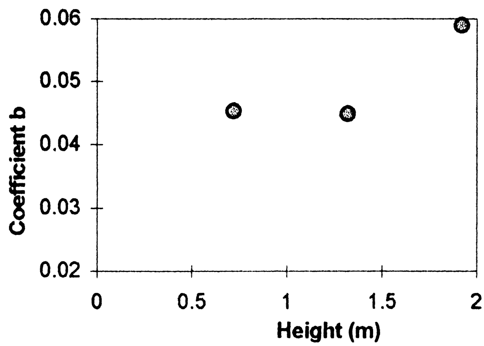


Fig. 3. Calculation of coefficients *a* and *b* for kerosene pool-fire.

4.2. Hexane pool-fire (4 m^2)

The same procedure was applied to the experimental data obtained with hexane pool-fires. Finally, the following expression relating flame temperature with height and time was obtained:

$$T_f(t,h) = \frac{t}{0.000851 \cdot t + 0.021 \cdot h + 0.0034} \tag{4}$$

The values predicted by this equation show the same trend as the experimental results (Fig. 5). However, Eq. (4) tends to underestimate the flame temperature by almost 100 K. Once again, this equation can not be applied to the first few seconds as there is a significant deviation.

5. Flame temperature correction

Although Eqs. (3) and (4) fit the experimental data relatively well, the predicted values (for example, 957 K at a height of 0.72 m) seem to be rather low compared to the

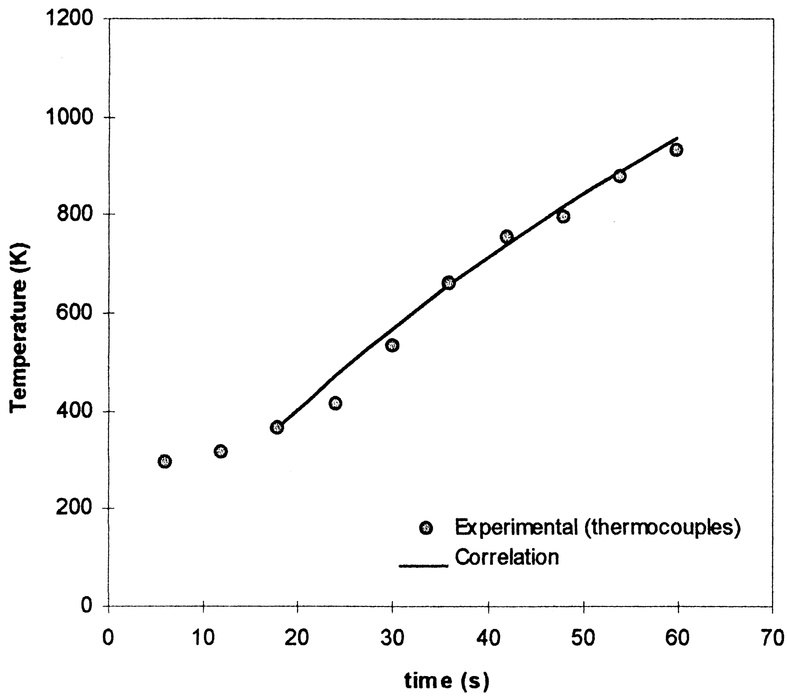


Fig. 4. Evolution of flame temperature as a function of time, at a height of 0.72 m from pool surface (kerosene pool-fire, 12 m^2).

results obtained by other authors [5,6]: 1150 K after 1 min at a greater height, 1.42 m. This seems to indicate that the values measured by plate thermocouples underestimate the real temperature at that point. According to Gregory et al. [6], thermocouples used to measure flame temperature always give values below those really existing in the flame. The most important reason for this error is the loss of heat from the thermocouple by radiation; the error becomes more important as the thermocouple is placed closer to the tank as the tank is a large and relatively cool object. In this work, the thermocouples were located on the external surface of the tank.

These results make evident the difficulty which is found when one attempts to measure the flame temperature of a large fire.

The measurements from a radiometer located at a certain distance from the fire (Fig. 1b), were used to correct this influence. The heat received by this radiometer can be calculated from the following expression:

$$Q = \tau F \sigma \left(T_f^4 - T_a^4 \right) \tag{5}$$

where F is the view factor, which is a function of the flame shape and size and of the distance between the radiometer and the fire. Eq. (5) was obtained assuming the fire as a

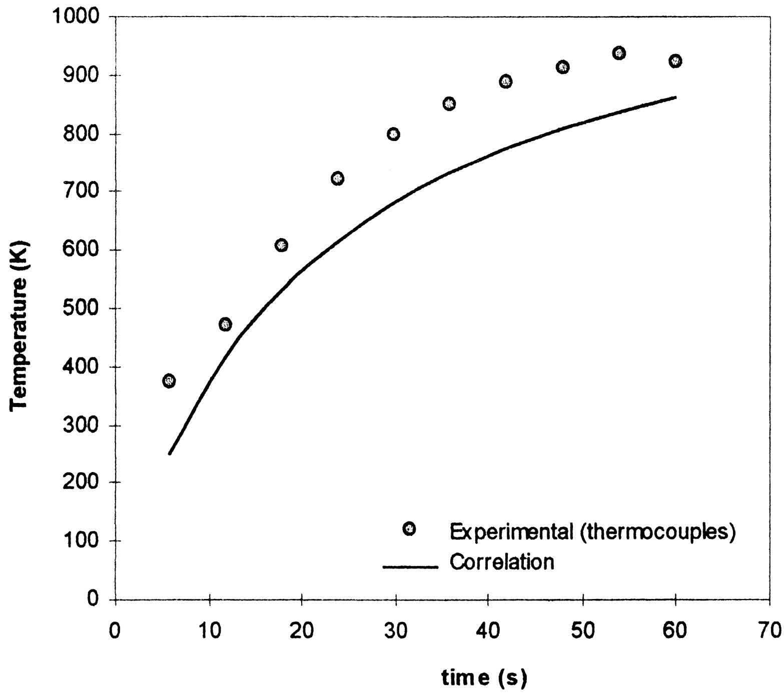


Fig. 5. Evolution of flame temperature as a function of time, at a height of 0.72 m from pool surface (hexane, 4 m^2).

surface emitter with an emissivity of one. τ is the atmospheric transmissivity, which is a function of the humidity of air [7],

$$\tau = 2.02(P_w x)^{-0.09}$$
$$P_w = \frac{H_R}{100}\exp\left(14.4114 - \frac{5328}{T_a(K)}\right) \quad (6)$$

Finally,

$$T_f = \sqrt[4]{\frac{Q}{\tau F \sigma} + T_a^4} \quad (7)$$

The temperature thus obtained corresponds to an average value for the whole flame, as the radiometer does not measure the radiation from a single point but from all the flame surface which it 'sees'. Fig. 6 shows the evolution of this average temperature calculated from the radiometer readings and Eq. (7). It can be clearly seen that as the stationary state is reached the temperature tends to a constant value. This value should correspond to a flame temperature calculated as the average value of flame temperatures at bottom

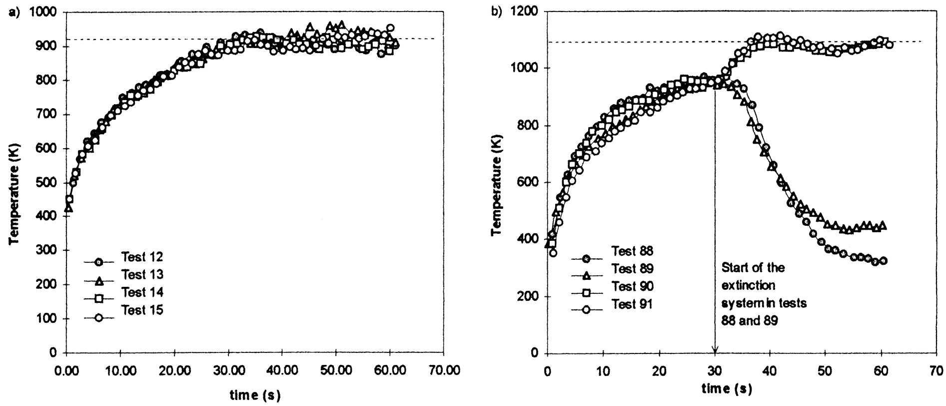


Fig. 6. Average flame temperature obtained from radiometer measurement. (a) Hexane pool-fire (4 m^2). (b) Kerosene pool-fire (12 m^2).

and top of the flame at $t \approx 60$ s (when the steady-state is reached). It should be noted that in tests number 88 and 89 activation of the extinction system implied a decrease in the radiation, and consequently in the temperature.

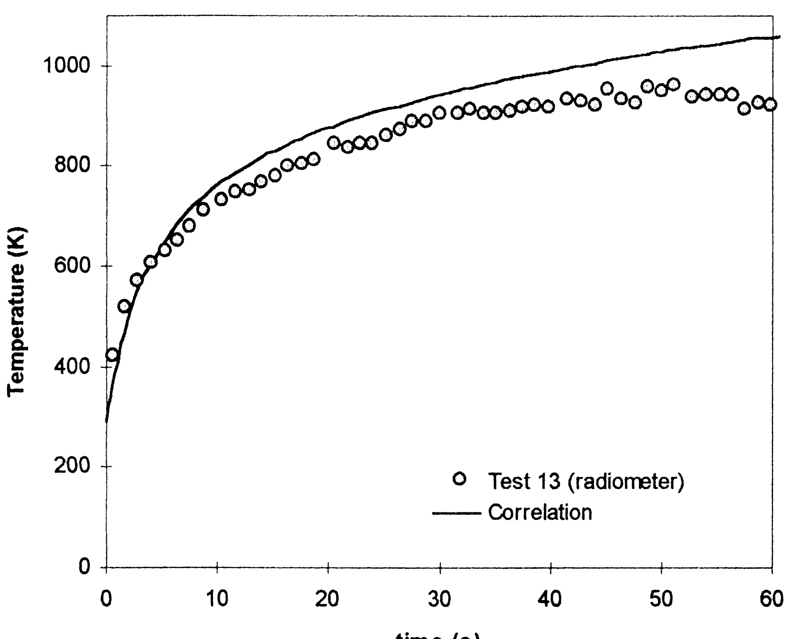


Fig. 7. Evolution of flame temperature as a function of time, from radiometer measurements and as predicted by Eq. (9) (as the average value of flame temperatures at bottom and top of the flame).

Taking this into account, together with the fact that at $t=0$ the temperature should be room temperature, Eqs. (3) and (4) were finally corrected to:

$$T_f(t,h) = \frac{t}{(0.000465 - 0.000188 \cdot h) \cdot t + 0.0114 \cdot h + 0.0347} + 290 \quad (8)$$

$$T_f(t,h) = \frac{t}{0.000851 \cdot t + 0.021 \cdot h + 0.0034} + 290 \quad (9)$$

The values predicted by these expressions have been compared with the experimental values. In Fig. 7, Eq. (9) has been plotted together with the radiometer measurements corresponding to test number 13. The agreement is fairly good. However, in the case of kerosene pools (12 m^2) the values predicted by Eq. (8) were significantly lower than the experimental results measured by the radiometer; the difference could be attributed to the fact that due to the larger size of the flame, the experimental values were not representative. Nevertheless, when the correction was not introduced, the prediction and the experimental values from thermocouples agreed very well.

6. Conclusions

The experimental results have shown how flame temperature evolves during the first step of a fire, until reaching an essentially constant value when the fire is completely developed. This first step can be very important in certain emergencies, and nevertheless it had been neglected by many authors.

Furthermore, these results have also proved that for certain fire sizes, flame temperature is not constant over all the fire. In the case of hexane pool-fires (4 m^2), flame temperature decreases with height. A correlation (Eq. (9)) has been obtained which predicts fairly well this behaviour.

However, for larger fires (kerosene, 12 m^2) the experimental values of flame temperature did not change with height according to any definite pattern. This behaviour, which does not correspond with what can be theoretically predicted, should be attributed to both the higher turbulence existing in these larger fires and to the fact that the measuring points in the experimental facility used, were located in such a position that they covered only a limited zone of the fire.

This work has also shown the difficulty which is found when one tries to measure the flame temperature over different points of a large fire.

The approach of this communication can be considered a step forward in the mathematical modelling of pool fires: in the attempts made by different authors to transfer the main features of these fires to a set of equations, most of them made the simplifying assumption of flame temperature being constant with height. However this is not true. Eq. (9) allows the prediction of results—for 4 m^2 pool fires—which are much closer to the real situation.

It should be observed that, when there is equipment engulfed in the fire, this equipment has a hindering or obstructing effect on the fire. To take this effect into account, a 'hindering factor' has been proposed (Planas-Cuchi et al. [3]) as the ratio between the heat released in the combustion of a pool fire with an obstacle and that released in the same pool fire with a free surface. As this factor leads to a lower combustion efficiency, it can be supposed that this will have an influence on the flame temperature distribution.

A research effort should be developed to find a more general model which could be applied to a wider range of fire sizes. An experimental project is being conducted at UPC with this objective.

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